Key Proton Test Findings for Sensor Technologies Evaluated in FY03

1. CIDTEC 818

Charge injection device (CID) technology is investigated by the Mission Research Corporation (MRC) as a niche application. The CID was a product of a development effort initiated by the Jet Propulsion Laboratory, under the Europa Orbiter program, which required a highly radiation- tolerant imager that could withstand the high-energy electron environment around Jupiter. The devices do not have nearly the performance of a charge coupled device (CCD) but they have the advantage that they are not subject to the charge transfer efficiency degradation that is so critical to CCD performance in space. CIDs have also been built which have high total ionizing dose tolerance. On the downside, CIDs have a higher read noise inherent in the design in which the output amplifier must ”see” the capacitance of the entire device, whereas the CCD has a very low read noise due to a small readout capacitor. Also there is only one vendor for CID technology.

The CID816 is a frontside illuminated pre-amplifier per column design variation of the charge injection device (CID) manufactured by CIDTEC. MRC and NASA-GSFC collaborated to proton test the device. The pre-irradiation read noise is 200 electrons at 50 kHz. No increase in the read noise was observed out to ~30 krad(Si) although there was a significant increase in the read fixed pattern noise[1] and nonlinearity beginning around 20 krad(Si). These increases are attributed to changes in the operating point of the readout amplifiers. The transient response to radiation is consistent with that expected for the active region size, and is similar to that seen for other unthinned devices of other types (e.g.: CCDs, APSs, hybridized PN junctions).

For more information, please see “Advanced charge injection devices for space instruments,” Kyle Miller and Kathy Doughty, to be published in the SPIE Astronomical Telescopes and Instrumentation Proceedings, August 2003.

2. HgCdTe Hybrid at >11 µm

Our test article is a large-format HgCdTe LWIR HgCdTe focal plane assembly with a pixel pitch of 60 µm and a cutoff wavelength exceeding 11 µm. It is a state-of-the-art detector but has not been selected as a flight candidate for any NASA programs. The detectors were grown by molecular-beam epitaxy (MBE) on CdZnTe substrates using a planarized double layer heterojunction design. As depicted in Figure 1, the detectors utilize lateral collection diodes so that only the

[1] The read fixed pattern noise is a measurement of the spatial variation of read noise measured across all pixels.

implanted diode volume relies on charge collection by drift, and charge collection from the surrounding material is due to diffusion charge that reaches the central volume from lateral and from vertical diffusion. The implanted diode has a 14 μm diameter and nominal 1 μm thickness, and the remaining (vast majority) of the pixel volume is considered to be field free.

The small size of the pixel's collection diode would normally result in very poor quantum efficiency. However in our case each pixel incorporates a micro-lens structure to focus light across the spectral band of interest to the pixel's central collection volume. This structure helps solve one of the most troubling problems in producing LWIR detectors since defects located in the pixel's field free regions do not compromise the dark current and operability of the array. Using this structure the detector quantum efficiency is 54% (in the absence of any antireflective coatings) based on measurements of the focal plane output versus photon irradiance. The median pre-irradiation pixel dark current is <0.05 pA at 40 K and the array has excellent responsivity uniformity (sigma/mean ~ 4%).

The practical consequences of charge sharing in this lateral diffusion based structure are especially important in comparison to the expected cross-talk characteristics of the more traditional HgCdTe diode architecture. Typically the entire diode area is covered by a thin (~1 μm) diode with a thicker (~10 μm) field free region underneath, and the IR response relies almost exclusively on vertical diffusion. In comparing our case of 60 μm pitch and 16 μm diffusion length, we see that 78% of the pixel area is within 1 diffusion length of a neighboring pixel's boundary and also its depletion volume. The expected charge sharing from particle transients consequently approaches 100% in the sense that nearly every hit will involve multiple pixels. For the lateral collection device we tested, whether we use number of pixels or amount of charge as a metric, our measurements indicate less than 15% cross-talk in all cases. Consequently, we recognize the lateral collection approach as a tremendous advantage in this regard, and the number of corrupted pixels due to particle strikes should be reduced substantially.

For more information, please see "Proton-Induced Transients and Charge Collection Measurements in a LWIR HgCdTe Focal Plane Array," Paul W. Marshall, John E. Hubbs, Douglas C. Arrington, Cheryl J. Marshall, Robert A. Reed, George Gee, James C. Pickel, and Rodolfo A. Ramos, to be published in the Dec. 2003 IEEE Transactions on Nuclear Science.

3. <u>HST Wide Field Camera 3 E2V Charge Coupled Device (CCD)</u>

The n-CCD has a format of 2048 x 4096 pixels with a 15 μm pixel size, a supplemental buried channel, a multi-phase pinned implant, and is backside illuminated. The detector response was evaluated for a range of 63 MeV proton fluences from 1 x 10^3 cm^{-2} to 2.5 x 10^9 cm^{-2} for a range of beam intensities. The devices were irradiated while operating inside a dewar, and annealing measurements were made as a function of time and temperature from -83 °C to +30°C. Only data from each temperature extreme has been analyzed to date.

The primary purpose of the study was to evaluate the formation and annealing of 'hot pixels'. Several instruments on board the HST have lost ~10% of their observing time as a consequence of monthy anneals to ambient temperatures in order to anneal hot pixels. It is very important to define 'hot pixel' precisely. For example, HST Advanced Camera for Surveys (ACS) reported a prelaunch mean dark current of 9.25 +/- 1.02 e^-/pixel/hr based on 4 1000 s frames. They used 12 times the average standard deviation of the dark distribution, or 144 e^-/pixel/hr as the threshold for hot pixel formation. In contrast the WFC3 E2V CCD43s have <0.1 e^-/pixel/hr dark currents at -83°C and the ACS threshold criteria would lead to a WFC3 threshold of only 13.5 e^-/pixel/hr. Since the readout noise on the WFC3 CCD is 3 e- and the threshold should be significantly higher than 5 sigma to avoid false positive, the WFC3 team used fixed rates to define the hot pixel thresholds. The WFC3 dark current requirement is <20 e^- at -83°C , so hot pixel thresholds of 20, 40, 80, 160 and 144 e^-/pixel/hr were studied. (For the room temperature portion of this study, the hot pixel threshold was defined as the mean plus 5, 10, or 15 times the standard deviation.)

The mean dark current rate change (from 0.07 to 2 e^-/pixel/hr) after 2.5 x 109 cm-2 is very modest and well below the requirement of <20 e^-/pixel/hr at -83°C. Hot pixels were introduced at a rate of 1200-2400 per month depending on the threshold. The upper and lower bounds for annealing rates at +30°C was determined to be 80-97%. At these rates the number of hot pixels after 5 years on orbit is expected to be between 0.5 to 5%. The difference in the shape of the dark current distribution (pre- and post-anneal) was very significant, indicating that the annealing rates vary substantially over the range of signal levels. The pronounced temperature dependence of the hot pixels at any threshold argues that the CCD should be operated at as cold a temperature as possible. This temperature dependence, as well as the impact of threshold selection, makes it quite difficult to compare results between instruments. Nevertheless the excellent annealing we observed on the WFC3 CCD show that a monthly soak at +30°C is an effective mitigation for the hot pixel problem. Finally, we note that the community still does not understand the behavior of the hot pixels in terms of expected defect properties.

For more details, see "Hot pixel behavior in WFC3 CCD detectors irradiated under operational conditions," Elizabeth J. Polidan, Augustyn Waczynski, Paul W. Marshall, Scott D. Johnson, Cheryl Marshall, Robert A. Reed, Randy A. Kimble, Gregory Delo, David Schlossberg, Anne Marie Russell, Terry Beck, Yiting Wen, John Yagelowich, Robert J. Hill, and Edward J. Wassell, to be published in the SPIE Astronomical Telescopes and Instrumentation Proceedings, August 2003.

4. HST Wide Field Camera 3 1.7 μm Rockwell HgCdTe FPA

The Rockwell 1024 x 1024 detector is a 1.7 μm cutoff HgCdTe sensor with a molecular beam epitaxially grown CdZnTe substrate hybridized to a Si multiplexer. The readout circuit is divided into four independent quadrants. The format of the device is 1024 x 1024 with five rows and five columns configured as reference pixels. The reference pixels are used to correct for baseline instabilities. The pixel size is 18 μm squared.

Pre-irradiation characterization included measurements of the detector's dark current, dark current stability, and noise in the radiation test dewar. Dark current was typically measured by sampling up the ramp for a 30 minute exposure with 16 frames. The dark current was 0.12 e-/s including a thermal leak of ~0.05 e-/s. The device underwent a series of 63 MeV exposures while actively running in the dewar at 150 K. The dewar was designed to minimized proton-induced activation.

Single event transient measurements were acquired. On average, about 30% of the signal charge diffused from the central pixel to the closet neighbors. This is not unexpected given the small pixel size and the random position of the proton hits with in the pixel. No significant persistence was noted.

No permanent effects on the WFC3 detectors were observed for the one month, 1 year or 5 year equivalent total exposure levels (the later being 5 x 10^9 cm^{-2} at 63 MeV). A temporary increase in dark current was observed after intermediate exposures and began to decay which held at 150 K. Warming the detector to 190 K reduced dark currents further. Other radiation effects such as increases in the hot pixel population and bias instabilities were temporary and also decayed with time and temperature. The bias level drift was tracked by the reference pixels and corrections can be made using these pixels. This should allow for useful operation of the device even in the presence of a radiation-induced bias shift.

Given that the fluence increments occur over time scales significantly shorter than would be experienced on orbit, the observed effects should be greatly reduced. Also, the IR instrument will periodically be warmed up to ~190 K which will accelerate the annealing process. In an unlikely worse case scenario, the instrument can be commanded to warm up to room temperature.

For more details, see "Radiation effects in WFC3 IR Detectors," Scott D. Johnson, Augustyn Waczynski, Paul Marshall, Elizabeth Polidan, Cheryl Marshall, Robert Reed, Randy A. Kimble, Gregory Delo, David Schlossberg, Anne Marie Russell, Terry Beck, Yiting Wen, John Yagelowich, Robert J. Hill, Edward J. Wassell, and Edward Cheng, to be published in the SPIE Astronomical Telescopes and Instrumentation Proceedings, August 2003.

5. Proton Response of James Webb Space Telescope (JWST) MWIR Hybrids

Both the Raytheon InSb detector (30 K) and the Rockwell HgCdTe detector (37 K and 5 μm cutoff) were all engineering grade prototypes.

The Raytheon SB291 readout multiplexor is a 1024 x 1024 element source-follower-per-detector (SFD) design formed on an epitaxially grown layer on a Si substrate. It has a 25 μm pixel and includes a column of reference unit cells on either side of the readout that serve to provide a 'black level' that may be used to subtract offset drifts in long-integration measurements.

The Rockwell H-1RG readout multiplexer is also an SFD design with an addressable area of 1024 x 1024 including a four pixel wide border of reference pixels. As with the Raytheon ROIC, input and output lines are restricted to one edge to make it three side buttable. An H-2RG (2048 x 2048) was also tested.

Overall transient responses are similar at Sensor Chip Assembly (SCA) level though Rockwell SCA hits are slightly larger (apparently due to detector). ReadOut IC (ROIC) hits are larger for SB291 than H1RG whereas H1RG proton crosstalk is significantly worse (probably related to smaller pixel pitch).

The dark current response is emphasized since it is likely to be the parameter that limits instrument sensitivity. These detectors had exceptional dark currents which made them a challenge to evaluate. Baseline pre-irradiation dark currents are on the order of millielectrons per second, necessitating very long integrations in 'perfectly' dark cryostats. Data artifacts due to amplifier drifts, terrestrial cosmic ray hits, and (after irradiation) induced radioactivity in the cryostat must be accurately subtracted. The dewar was carefully designed to minimize activation during proton exposures, and also had the capability to assess secondary production as described in the references below.

After 5 krad(Si) exposure with 63 MeV protons, both the Raytheon and Rockwell devices lost about 10% of pixels, with this percentage of hot pixels not being strongly dependent on threshold levels over a reasonable range. To be counted as a hot pixel, it had to fall below a very tight threshold every time it was measured prior to irradiation, and then exceed a larger 6 σ threshold value at least 11 times out of 13 measurements after irradiation exposure. This degree of dark current activation is within a factor of two of the JWST NIR operability requirements. It is important to note that the accelerator deposits the dose over a very short period of time as compared to the on-orbit case, and that annealing in the later case might make the difference between meeting the requirement or not.

Most other performance parameters (e.g. read noise, amplifier linearity, and power dissipation) were unchanged after 5 krad(Si). These parameters are largely dependent on the readout operation which was not significantly affected by the 5 krad(Si) dose level. However a substantial difference in the inherent hardness of the two ROICs was observed, with the Rockwell readout showing an offset shift with dose that was more than 40 times that of the Raytheon part.

For more information, please see “Radiation environment performance of JWST prototype FPAs,” M.E. McKelvey, K.A. Ennico, R.R. Johnson, P.W. Marshall, R.E. McMurray, Jr., C.R. McCreight, J.C. Pickel, and R.A. Reed, to be published in the SPIE Astronomical Telescopes and Instrumentation Proceedings, August 2003. The impact of secondary production on proton testing is discussed in J. Pickel, R.A.Reed, P.W.Marshall, T.M.Jordan, G.Gee, B.Fodness, M.McKelvey, R.E.McMurray, K.A.Ennico, R.R.Johnson and C.McCreight, “Proton-Induced Secondary Particle Environment for Space-Based Infrared Sensors”, to be published in the Dec. 2003 IEEE Transactions on Nuclear Science. For further information about the transient response of the JWST prototype detectors please contact Robert Reed at robert.a.reed@gsfc.nasa.gov.